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Final Technical Report

AFOSR Grant No. F49620-00-1-0236

Instrumentation for Advanced, Slow-wave, microwave vacuum electron device research and graduate education

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DURIP Final Report

Part 1: Instrumentation for studies of nonlinearities in advanced TWTs

Introduction

Due to their superior combinations of efficiency, low signal distortion ("linearity"), power, compact size and weight, and large bandwidths, vacuum electronic traveling wave tube (TWT) devices represent the favored transmitter technologies in most currently deployed US military communications, electronics warfare, electronics counter measures, and radar systems. Next generation applications, however, include ambitious plans requiring even lower distortion characteristics, greater efficiency, larger bandwidths, and, in some cases, higher frequencies. Improved understanding of the nonlinear behavior of TWT vacuum electronic devices will enable new approaches to TWT design and systems implementation to meet the desires for higher data rate transmission at equal or lower cost. The equipment purchased with this DURIP grant has made possible new capabilities for fundamental research of vacuum electronics to support next generation U.S. military defense needs and objectives.

Summary of Purchased Equipment

The two Agilent 83626B digital signal generators and the Agilent 86100A wideband oscilloscope provide numerous experimental opportunities that were previously unrealizable. The broad frequency range of the signal generators (10 MHz – 20 GHz) allows the research TWT to be excited in new ways that offer additional experimental insight. Using one generator, a single input tone has been swept in frequency and power, to better characterize the response of the XWING TWT. By connecting the two generators together, the signals can be "phase-locked," allowing multi-tone excitations of the TWT. Two closely spaced tones, one at 2.00 GHz and another at 2.15 GHz within the bandwidth of the TWT, have been used to investigate the third-order intermodulation distortion products that arise in the output spectrum. Additionally, a technique for suppressing these effects by –22 dB has been demonstrated by injecting a low-level signal with the appropriate phase at twice the frequency of the 2.00 GHz fundamental signal. The broad frequency range and phase-locking feature of the Agilent 83626B signal generators make these experiments possible which we could not have performed without the new equipment. These results are important and relate to important issues for broadband communications.

The Agilent 86100A wideband oscilloscope offers the ability to capture high frequency waveforms up to 50 GHz. A time-gated, data acquisition mode is critical for capturing XWING TWT output waveforms, since this tube is operated in a low duty-cycle, pulsed mode. The oscilloscope has been used to observe the phase relation between multiple input signals, and to measure the propagation times of RF waves along the TWT helix. These capabilities are crucial for the multi-tone and phase velocity investigations that are currently underway.

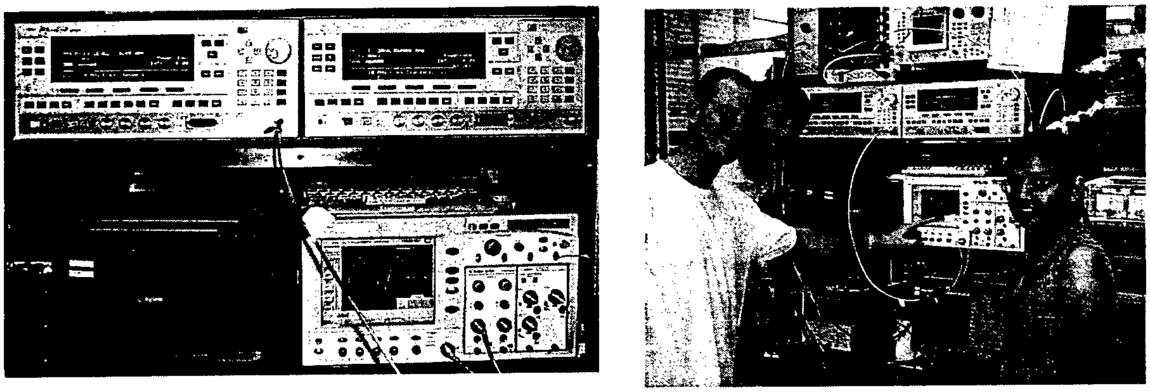


Figure 1: Laboratory photos of two Agilent 83626B signal generators and one Agilent 86100A wideband oscilloscope. These instruments are currently used with the XWING TWT, for a variety of experiments that address important issues in our research objective of achieving multi-tone linear amplification in wide band traveling wave tubes.

Illustrative Application of the Equipment

As an illustrative application of the equipment for research purposes, we attach a draft manuscript for a brief report on a recent, important research breakthrough. This brief is enclosed as the next several pages of this report.

Third-Order Intermodulation Reduction by Harmonic Injection in a TWT Amplifier

Michael Wirth, Aarti Singh, John Scharer, *Senior-Member, IEEE*, and John Booske, *Senior-Member, IEEE*

Abstract—**A method for reducing the two-tone third-order intermodulation products arising from two carrier frequencies at 1.95 and 2.00 GHz is demonstrated in a travelling wave tube distributed amplifier. The optimum amplitude and phase of an injected second harmonic and the resulting intermodulation suppression, of upto 24.2 dB, are examined for fundamental drive levels approaching saturation.**

Index terms—**harmonic injection, traveling wave tube, IM3, nonlinear distortion**

Introduction

When multiple carrier frequencies are amplified in a traveling wave tube (TWT) or other non-linear amplifier, various order intermodulation products (IMPs) arise from the sum and difference of these frequencies. Certain IMPs are of concern since they lie close to the fundamental tones being amplified, thereby limiting the useful bandwidth of the amplifier. For example, in a simple excitation of f_1 and f_2, the two-tone third-order intermodulation products (IM3s) arise from $2f_1$-f_2 and $2f_2$-f_1, whereas IM5s with nearby frequencies arise from $3f_1$-$2f_2$ and $3f_2$-$2f_1$. The work described here injects an additional signal into a TWT at the frequency of the second harmonic of the upper fundamental drive tone (f_2). When this injected signal at $2f_2$ is of the proper phase and amplitude, a significant reduction in the upper IM3 ($2f_2$-f_1) is observed.

This is the first experimental examination of IM3 reduction using the harmonic injection technique in a TWT distributed amplifier. A recent study by Aitchison *et al.* [1] has demonstrated the effectiveness of this technique in narrowband, solid-state amplifiers at 835 and 880 MHz. They obtain substantial reduction in IM3 levels by both second harmonic and difference-frequency (1 MHz) injection techniques. Work by Datta *et al.* [2] and Wohlbier [3] describe theoretical models that predict similar behavior in TWTs. This behavior has been observed [4] but not published nor studied in detail. Additionally, the sensitivity of IM3 reduction to the injected harmonic's amplitude and phase is also explored.

M. Wirth and A. Singh are graduate students, while J. Scharer, and J. Booske are Professors with the Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, WI 53706 USA (e-mail: scharer@cptc.wisc.edu).

We gratefully acknowledge support in part by AFOSR Grant 49620-00-1-0088 and by DUSD (S&T) under the Innovative Microwave Vacuum Electronics Multidisciplinary University Research Initiative (MURI) program, managed by the United States Air Force Office of Scientific Research under Grant F49620-99-1-0297 and also the University of Wisconsin, Madison.

Experimental Device and Setup

Description of XWING TWT

The TWT used in this investigation, termed the XWING TWT (for eXperimental WIsconsin Northrop Grumman TWT), is a research version of a product manufactured by Northrop Grumman. This two-stage, helical TWT provides a moderate gain of 20-30 dB over a frequency range of 2-6 GHz. In the following experiments, fundamental tone output levels are in the range of 33-37 dBm.

Experimental Setup

To maintain precise frequency and phase relationships, three frequency synthesizers were used to supply the two fundamental tones and the harmonic. Since the phase of the injected harmonic must be referenced with respect to the higher frequency fundamental, two Agilent 83623B synthesizers were configured to share a common 10 MHz phase reference signal.

The upper fundamental and harmonic frequencies were set to 2.00 and 4.00 GHz, respectively. The 4.00 GHz signal was sent through a Narda 3752 phase shifter, allowing the fundamental-to-second harmonic phase relationship to be adjusted in real-time. The lower fundamental frequency of 1.95 GHz was supplied by a Wavetek 3520 synthesizer, providing a 50 MHz difference between the two drive tones. The phase of this fundamental was not referenced to any other signal.

The phase relationship between the upper fundamental and the injected harmonic was monitored on two Agilent 86100A wide-bandwidth oscilloscopes. A schematic of the TWT input network is shown in Fig. 1.

Experimental Procedures and Results

15 dBm/tone Fundamental Drive Levels

First, the 1.95 and 2.00 GHz fundamental drive tones were independently set to 15 dBm/tone at the TWT input tap, and the output spectrum was captured on an Agilent E4407B digital spectrum analyzer. This TWT output spectrum is shown in Fig. 2a. Next, the 4.00 GHz second harmonic tone was injected at the TWT input and the phase was varied, with respect to the 2.00 GHz fundamental, to achieve the lowest IM3 level.

With the phase relationship optimized, the injected harmonic amplitude was varied until a maximum suppression in the upper IM3 level was observed. This occurred with an injected harmonic amplitude of -2.1 dBm or 17.1 dB below f_2. The optimized TWT output spectrum is shown in Fig. 2b. Notice that the upper IM3 is reduced by 21.3 dB, yielding an upper carrier to IM3 power ratio of 43.9 dB. The sensitivity of the IM3 level to variations in the injected harmonic amplitude and phase is shown in Fig. 3. In all cases, the IM3 power was measured to within an accuracy of 0.2 dBm.

18 dBm/tone Fundamental Drive Levels

The experiment was repeated at higher input drive levels of 18 dBm/tone. The upper and lower fundamental tones were amplified by separate solid-state amplifiers (DBS DB94-0373 and Mini-Circuits ZHL-42W). Preamplifier harmonic content was verified at 30 dB below the carrier. Similar procedures were followed to determine the optimum phase and amplitude for the injected harmonic. For the optimum case, an IM3 reduction of 24.2 dB was observed, corresponding to an injected harmonic drive level of 0.9 dBm, or 17.1 dB below f_2. The IM3 suppression is greater than in the previous case, since the TWT is operating closer to saturation and nonlinear distortions are more pronounced. Consistent with the previous case, the improved upper carrier to IM3 power ratio is 43.6 dB. The optimum phase relationship between the injected harmonic and upper fundamental was measured at the TWT input tap. The 4 GHz injected harmonic was found to lead the 2 GHz fundamental by 47.5 degrees, with respect to the 2 GHz fundamental period.

Conclusions

For two-tone excitation of a distributed TWT amplifier operating near 2 GHz with a 50 MHz separation, a significant reduction in the amplitude of the third-order intermodulation product was achieved by injecting at the second harmonic of one of the drive tones with an optimum amplitude and phase. Reductions of third-order intermodulation products of 21.3 and 24.2 dB were observed for two-tone fundamental drive levels of 15 and 18 dBm/tone, respectively. While this experiment focused on the reduction of the upper third-order intermodulation product, both may be reduced by adding another tone with the appropriate amplitude and phase at twice the lower fundamental frequency.

References

[1] C.S. Aitchison, M. Mbabele, M.R. Moazzam, D. Budimir and F. Ali, "Improvement of Third-Order Intermodulation Product of RF and Microwave Amplifiers by Injection," *IEEE Trans. on Microwave Theory and Techniques,* vol. 49, no. 6, pp. 1148-1154, June 2001.

[2] S.K. Datta, P.K. Jain and B.N. Basu, "Control of IM3 Distortion in Helix TWTs by Harmonic Injection – An Eulerian Hydrodynamical Study," *IEEE Trans. Electron Devices,* vol. 48, no. 1, pp. 62-67, January 2001.

[3] J. Wohlbier, University of Wisconsin - Madison, private communication (2001).

[4] C. Armstrong, Northrop Grumman Corporation, private communication (2001).

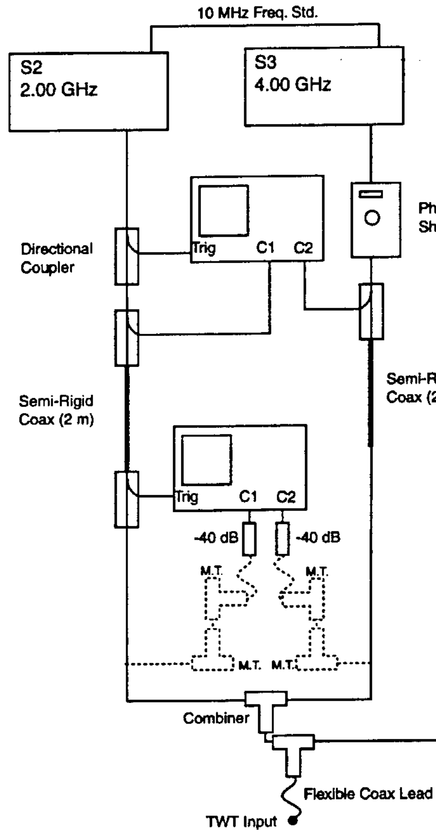


Fig. 1. Block diagram of single-harmonic injection experimental setup. Dashed lines show connections that were made with the TWT deactivated. Matched terminations (M.T.) were placed on open combiner ports.

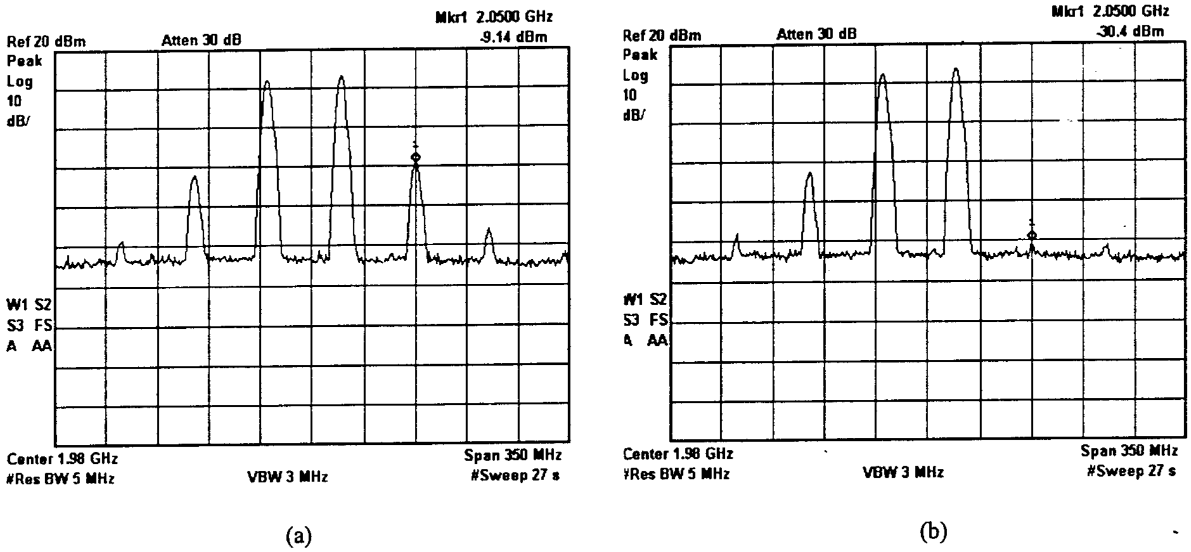
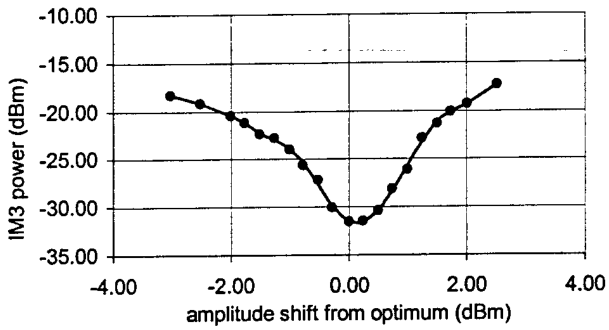
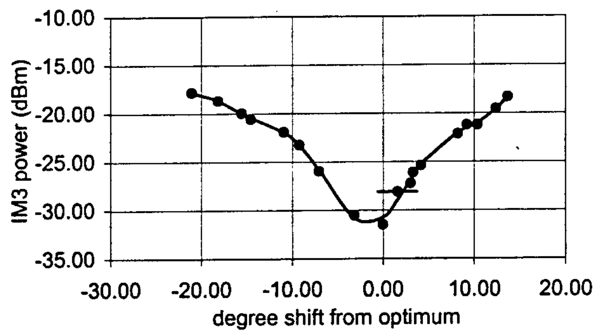


Fig. 2. TWT output spectrum for two-tone, 15 dBm/tone input: (a) without and (b) with harmonic injection technique showing 21.3 dB reduction in upper IM3 level.



(a)



(b)

Fig. 3. Sensitivity of IM3 suppression to: (a) variation in injected harmonic amplitude and (b) variation in injected harmonic phase, with respect to 2 GHz fundamental.

Part 2: Equipment for studies of noise mechanisms in magnetrons

The Microwave Spectrum Analyzer Agilent Model 8564EC) has been utilized to measure and characterize the noise performance of crossed field microwave devices. This research problem is very important tot he DoD because it determines the ultimate performance of defense systems from the Navy's Aegis Cruiser to the Patriot anti-missile defense system.

Specifically, the spectrum analyzer has successfully identified the quiet and noisy states of a kW (oven) magnetron, which is the source of this research. Figure 1 depicts the microwave spectrum measured by the DURIP spectrum analyzer from a kW magnetron signal while operating in what is believed to be the "quite" state. Notice that the spectrum is very narrow down to a noise floor some 65 dB below the signal peak.

Figure 2 shows data measured with the same Agilent Spectrum Analyzer for what we believe to be the "noisy state" of the kW magnetron. Here it can be seen that the microwave spectrum has become very wide, even beginning at 30 dB below the signal peak.

While the underlying causes of the magnetron quiet and noisy states are still under investigation, the excellent resolution of the Agilent Spectrum Analyzer is apparent from the data and provides a powerful tool for the understanding of this important problem of noise generation in DoD microwave systems.

MURI
Microwave Vacuum Electronics

Oven Magnetron Spectrum
Filament Power Supply Voltage: 105 VAC
Time Index: 002 × 15 sec
Date: June 08, 2001

Agilent 8564EC Spectrum Analyzer Settings:
Resolution Bandwidth: 100 kHz
Sweep Time: 12 sec
Attenuation: 30dB (Auto)

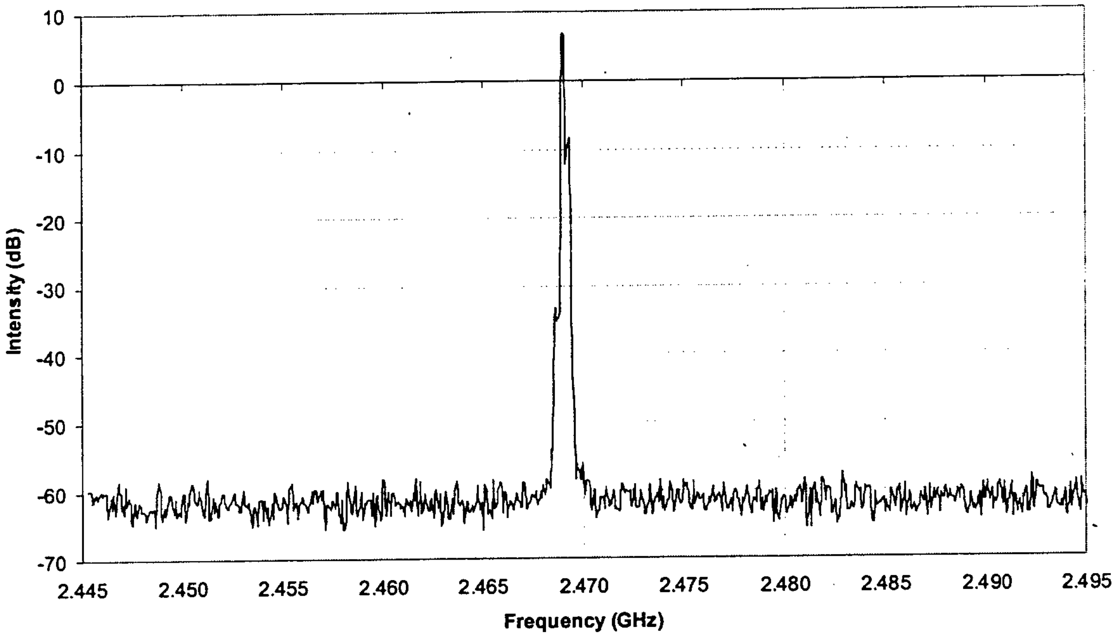


Figure 1.

MURI
Microwave Vacuum Electronics

Oven Magnetron Spectrum
Filament Power Supply Voltage: 105 VAC
Time Index 019 × 15 sec
Date: June 08, 2001

Agilent 8564EC Spectrum Analyzer Settings:
Resolution Bandwidth: 100 kHz
Sweep Time: 12 sec
Attenuation: 30dB (Auto)

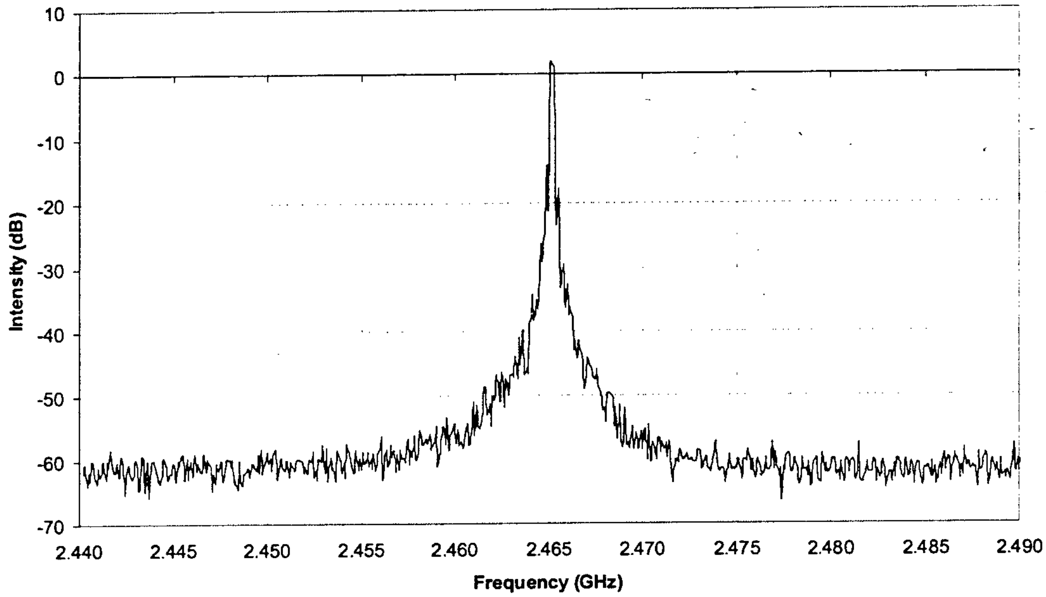


Figure 2.